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FIBER-REINFORCED POLYMER COMPOSITE MATERIALS FOR REHABILITATION OF REINFORCED CONCRETE STRUCTURES

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FIBER-REINFORCED POLYMER COMPOSITE MATERIALS FOR REHABILITATION OF REINFORCED CONCRETE STRUCTURES

INTRODUCTION

Fiber-reinforced polymer (FRP) composite materials provide an outstanding technique for rehabilitating and strengthening existing reinforced and prestressed concrete bridges, buildings and other structures. Whether a structure has been damaged due to overload, earthquake or material deterioration or whether the structure requires strengthening to resist increased future live loads, wind or seismic forces, FRPs provide an efficient, cost-effective and easy-to-construct means to reinforce concrete members. These advanced composites may be designed to act as flexural, shear and confinement reinforcement. They may be placed with less disturbance to building occupancy, bridge traffic and other functions as compared to rehabilitation using additional steel reinforcement.

The concept of strengthening with FRP was pioneered by Professor U. Meier, at the Swiss Federal Laboratories for Materials Testing and Research Institute in the early 1980's. His extensive research activities led to the first-time field implementation of FRP rehabilitation for both bridge and building applications. Both the Ibach bridge near Lucern, Switzerland, and the City Hall of Gossau St. Gall in northeastern Switzerland were strengthened in 1991 by bonding pultruded carbon fiber polymer plates to the exterior surfaces of the concrete structures. Details on some of these and other early applications are described by Meier et al. (1993). Since then, there has been a worldwide keen interest not only to utilize polymeric materials in strengthening structures but also to examine their structural behavior under a variety of loading and environ-

mental conditions. While a review highlighting some fundamental concepts pertaining to the use of FRP materials in structural rehabilitation is found in an article by Triantafillou (1998), comprehensive expositions of past research activities, test results, and case studies on the same subject are given in a recent monograph by Hollaway and Leeming (1999).

To effectively design and execute a rehabilitation scheme using FRPs, the engineer must fully understand the condition of the existing structure, the properties and characteristics of the composite materials, the interaction between the FRP and concrete, and construction methodology.

The terms Rehabilitation, Repair, and Strengthening are defined as follows:

- Rehabilitation: the process of repairing or modifying a structure to a desired useful condition.
- Repair: the process of replacing or correcting deteriorated, damaged or faulty materials, components, or elements of a structure.
- Strengthening: the process of increasing the load-carrying capacity of a structure or portion thereof.

STRUCTURAL ASSESSMENT

The structure must be evaluated prior to application of FRPs so that the actual load-carrying capacity may be determined and so that the causes for prior deterioration or damage may be identified and eliminated. Cracked, chipped and deteriorated concrete must be repaired; and corroded steel reinforcement must be cleaned and evaluated prior to further rehabilitation.

The first step of the structural assessment should be a review of the plans, specifications, and construction records of the structure. These documents provide the minimum strength of the concrete and of the reinforcement, the size of the members, and the size and location of all rein-

forcement. An analysis based upon these plans gives an estimate of the anticipated strength of the structure provided no deterioration has occurred.

The second step is site observation which includes measurement of the geometry of the structure and the determination of cracks and other deterioration or damage. The geometry is compared with the plans to assure the correctness of the documentation. Observation of cracks and damage provides a basis for the design of repairs needed prior to rehabilitation.

Provided that cracking and deterioration are not extensive, nondestructive testing of the structure is used to verify the strength of the concrete and the location of the reinforcement. Quality of the concrete can be investigated using acoustic impact (like chain dragging), rebound hammers (Schmidt Hammer shown in Figure 1) and penetration resistance (Windsor Probe). Magnetic detection devices (Pachometers) may be used to measure cover and location of reinforcement. If the quality of the concrete appears poor, then destructive tests are necessary. Cores are taken; cutting of reinforcement is avoided. Compression testing of the cores provides an acceptable determination of compressive strength (f'_c). Petrographic analysis is required if alkali-silica reaction is suspected of causing deterioration.

Cracking and/or pop-outs in the vicinity of reinforcement indicates potential corrosion of the reinforcement. In those locations, the concrete should be removed and the reinforcement inspected. If the reinforcement is rusted such that loose rust is noted, then the concrete must be removed from around the corroded reinforcing bars, and the bars must be cleaned of rust. The actual cross sectional area of the bars should be determined and used in subsequent analysis. Further, the chloride content of the concrete should be determined along with its electrical potential so that the probability of continued active corrosion is determined. Permitting active corrosion

of reinforcement to continue after FRP rehabilitation will limit the life of the rehabilitation system.

With the above assessment complete, areas of damaged and deteriorated concrete should be repaired prior to placement of FRP materials. Where concrete has been removed and corroded reinforcement cleaned, those areas should be patched with compatible materials. In general, Portland cement mortar patches provide good bond and compatibility with the existing concrete substrate. Polymer concretes are preferred for small patches (less than 20 mm thick).

Where damage has occurred due to overload, differential settlement, or restraint of shrinkage and creep of the concrete, cracks may be large. An assessment of those cracks may indicate that the concrete cannot transmit shear or compressive forces. In such cases, cracks with widths between 0.3 mm and 3.0 mm should be filled by injection with a low viscosity epoxy; cracks wider than 3.0 mm should be injected with either a polymer or cement grout. Wherever cracks are injected and patches are placed, the surface of resulting structure should be smooth and even so that the FRP may be applied satisfactorily.

Finally, the strength of the existing structure should be assessed based on the actual condition of the structure.

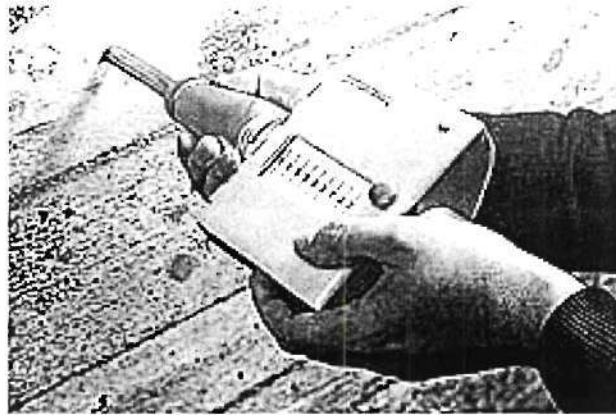


Figure 1. Schmidt Hammer (Courtesy of PROCEQ SA)

COMPOSITE MATERIALS REINFORCING SYSTEMS FOR CONCRETE STRENGTHENING

Fiber-reinforced polymer composites used for strengthening reinforced concrete structures are made of aramid, carbon or glass fibers with an epoxy thermoset resin matrix to bind them together. They can be classified into two systems:

1- Shop-manufactured composites: pre-manufactured composites in the form of plates, shells, or other shapes are bonded in the field to the surface the concrete member using structural adhesives. These composites are manufactured by a variety of techniques such as the pultrusion, filament winding, and resin transfer molding. Some of the common commercially available shop-manufactured composite systems are briefly described below:

- **CarboDur™:** CarboDur composites are 1.2 mm (0.5 in.) thick carbon/epoxy pultruded unidirectional plates that can be bonded to the concrete surface with an epoxy based adhesive (Sika Corporation). The fiber volume in this system is approximately 68%. (Figure 2)

- SnapTite™: This is a 3 mm (1/8 ") thick prefabricated E-glass/isophthalic polyester shell that can be bonded to a round concrete column using polyurethane adhesive. Additional shells can be bonded over the first bonded shell to achieve the desired thickness.
- Hardshell Structures: This is a prefabricated E-glass/vinylester shell manufactured by the vacuum-assisted resin transfer molding process with a fiber volume of about 60%. The shell can be bonded to a round concrete column using an adhesive system.

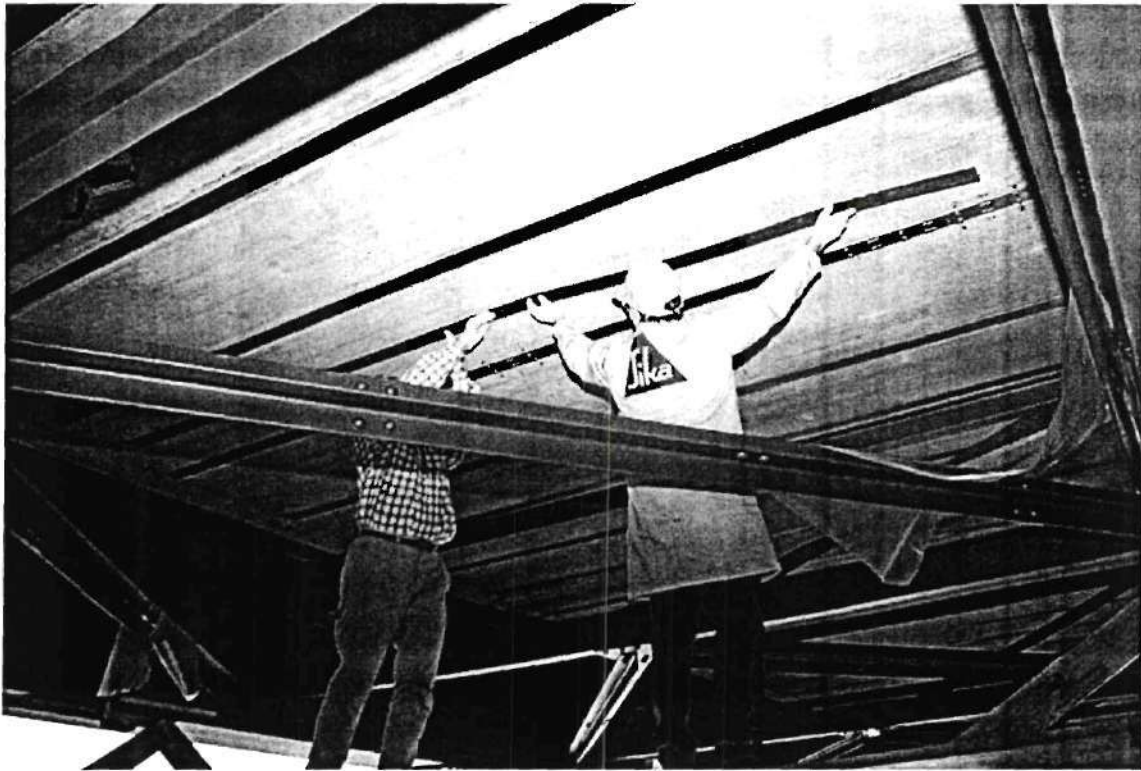


Figure 2. Application of shop-manufactured carbon composite plates to the underside of a bridge deck

2- Field-manufactured composites: fibers in the form of tows or fabrics are impregnated in the field and placed on the surface of the structure requiring strengthening. Methods of impregnation have been done manually (hand lay-up), by a portable impregnator machine, or infusion

under vacuum. The composite is bonded to the concrete and then left to cure under ambient or elevated temperature.

Commercially available field-manufactured composite systems include, but are not limited to:

- MBraceTM (Master Builders Inc.) and ReplarkTM (Mitsubishi Chemical Corporation) are similar systems that include a primer, putty, epoxy resin matrix, and dry unidirectional carbon fiber sheets weighing approximately 300 g/m² (8.8 oz/yd²). The composite reinforcing system is manufactured by the hand lay-up technique.
- SikaWrap[®] Hex (Sika Corporation) and TYFO[®] Fibrwrap[®] System (Fyfe Co. L.L.C.) are unidirectional fabrics weighing approximately 612 g/m² (18 oz/yd²). The fabrics are impregnated with epoxy resin using a portable impregnator machine as illustrated in Figure 3.
- XXsys Technologies, Inc system is one in which columns are wound with prepreg carbon tows using a ROBO-WRAPPERTM Winding Machine as shown in Figure 4. The resin is cured at elevated temperature using a portable oven known as ROBO-Curing SystemTM shown Figure 5.

An advantage of the shop-manufactured composites over the field-manufactured composites is the ability to control the quality and uniformity in the composite reinforcing systems. An advantage of the field-manufactured composites is their ability to conform to non-uniform concrete surfaces.

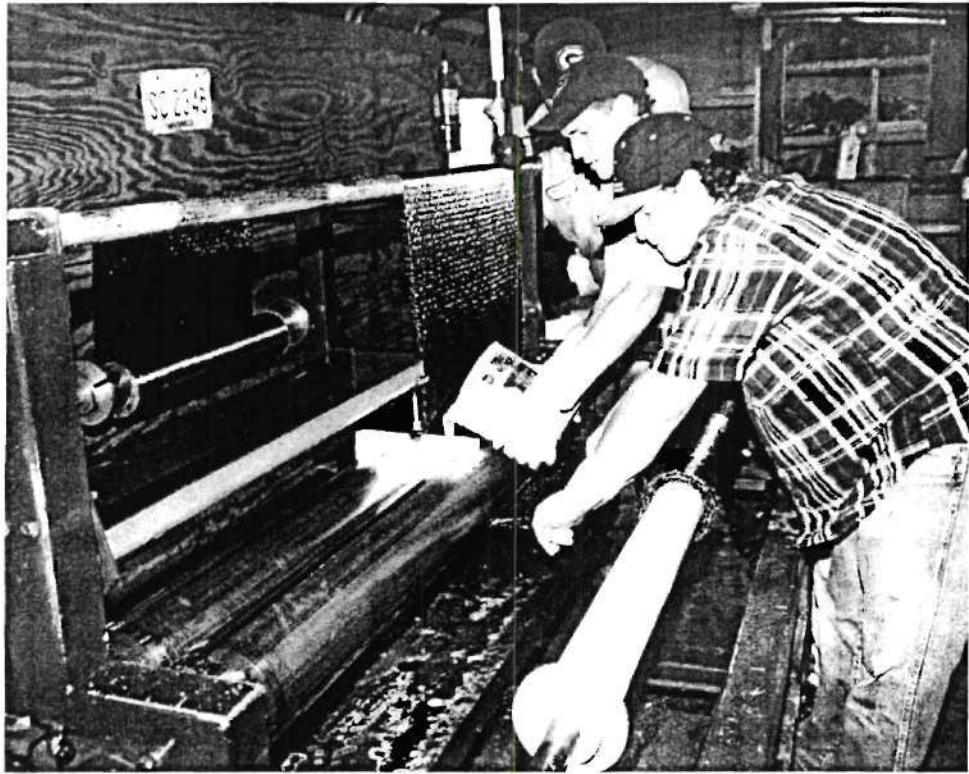


Figure 3. Portable impregnator machine

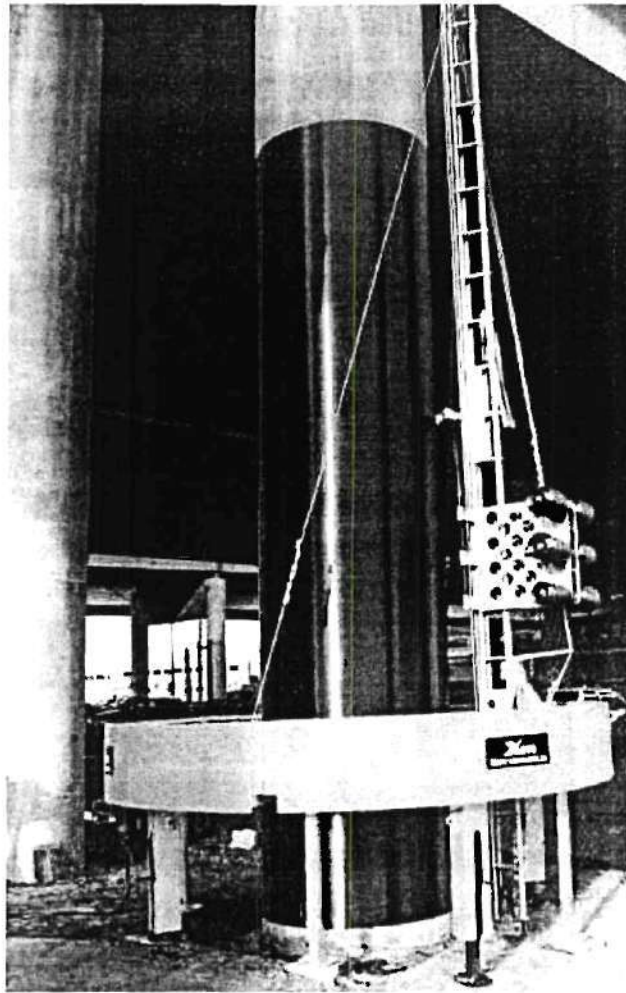


Figure 4. ROBO-WRAPPER™ Winding Machine (Courtesy of XXsys Technologies, Inc.)

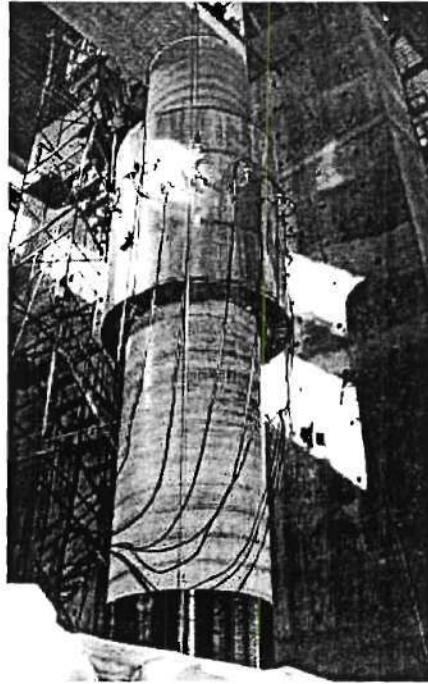


Figure 5. ROBO-Curing System™ (Courtesy of XXsys Technologies, Inc.)

PROPERTIES OF POLYMER COMPOSITE REINFORCING SYSTEMS

Because of the absence of national codes and standards, manufacturers report their data in a variety of ways. This variation presents both the engineer and the owner with a dilemma for properly comparing different systems and for assessing the benefit of using such materials in construction projects. Reported data should include the method of testing used to obtain such data, the number of tested specimens, the number of batches from which test specimens were drawn, the mean value, the minimum value and maximum value, and the coefficient of variation. Manufacturers also may elect to provide the minimum guaranteed property values along with the methods by which such values are obtained. As a minimum, the contractor should furnish the owner the following information pertaining to the matrix (binding resin or adhesive), reinforcement, and composite systems:

Matrix Material

19. The commercial designation, name of manufacturer, and Material Safety Data Sheet (MSDS), prepared in compliance with the Federal OSHA Hazard Communication Standard 29 CFR 1910.1200, of the matrix material and any of its component.
20. The density of the matrix material or any of its components determined according to ASTM D792 Test Methods for Specific Gravity and Density of Plastics by Displacement.
21. The gel time determined according to ASTM D2472 Standard Test Method for Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins.
22. The curing behavior determined according to ASTM D 4473 Standard Practice for Measuring the Cure Behavior of Thermosetting Resins Using Dynamic Mechanical Procedures.
23. The water absorption determined according to ASTM D 570 Standard Test Method for water Absorption of Plastics.
24. The glass transition temperature according to ASTM E 1356 Test Method for Glass Transition Temperatures by Differential Scanning Calorimetry or Differential Thermal Analysis.
25. The tensile properties according to ASTM D638 Standard Test Method for Tensile Properties of Plastics.
26. The compressive properties according to ASTM D695 Standard Test Method for Compressive Properties of Rigid Plastics.
27. The flexural properties according to ASTM D790 Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.

Reinforcement

1. The commercial designation, name of manufacturer, and fiber form (e.g. yarns, strands, tows, fabric, and prepreg), the fiber orientation, fiber dimensions, and fiber surface treatments.
2. The density of the fiber according to ASTM D 3800 Standard Test Method for Density of High-Modulus Fibers.
3. For preregs, the matrix solid content and matrix content shall be determined according to ASTM D3529 Standard Test Method for Matrix Solids Content and Matrix content of Composite Prepreg.
4. For epoxy/carbon fiber based prepreg, the volitiles content shall be reported according to ASTM D 3530 Volitiles Content of Carbon-Fiber Prepreg.

Composite System

For a composite system, cured under specified conditions approximating the conditions of the actual use, the following material properties determined experimentally should be provided:

1. The density according to ASTM D792 Test Methods for Specific Gravity and Density of Plastics by Displacements.
2. The tensile properties (ultimate strength, ultimate strain, and modulus) of the composite materials according to ASTM D3039 Test Method for Tensile Properties of Polymer Matrix Composite Materials.

3. The fiber volume according to ASTM D2584 Test Method for Ignition Loss of Cured Reinforced Resins.
4. The void volume according to ASTM D2734 Test Method for Void Content of Reinforced Plastics. D 3171 Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion.
5. Moisture diffusivity and absorption or desorption properties according to ASTM D5229 Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials.

The wealth of information gained from over 30 years of composite applications for aerospace use makes the task of reporting properties straightforward in the case of shop-manufactured composites. However, difficulties arise when composites are manufactured in the field, especially with the hand lay-up technique where both geometrical (e.g. thickness) and material properties (e.g. mechanical) are strongly influenced by not only the operator fabricating the composites but also by climate curing conditions, dust from occasional wind, and other environmental factors.

MATERIAL PROPERTY REQUIREMENTS FOR DESIGN

When used to strengthen concrete structures, polymeric composite reinforcing systems will virtually always be subjected to not only various combinations of loads (e.g. dead loads, live loads, wind loads, and earthquake loads) but also to complicated environmental exposures (ambient temperature, solar radiation, humidity, organic growth, chemicals, etc.) that change

continually. Therefore, the composite properties need to be stable or to change insignificantly during the lifetime of the structure.

Temperature is of particular importance. Defining the operating temperature range requires, of course, a proper examination of the climatological data for the location in which the structure is to be built. The data can be statistically analysed for trends and variations (see as an example Von Storch and Zwiers ,1999) so that high and low temperature values can be estimated for a region and time interval, which have a specified annual probability of being within the admissible range. Temperature records in the United States are readily available through the National Climatic Data Center (NCDC). As a first approximation, we will define the operating temperatures by the range bounded by the all-time daily temperature maximum and minimum recorded in a given location from the observed climate. Figures 6 and 7 show these extreme values for each state individually (Source NCDC).

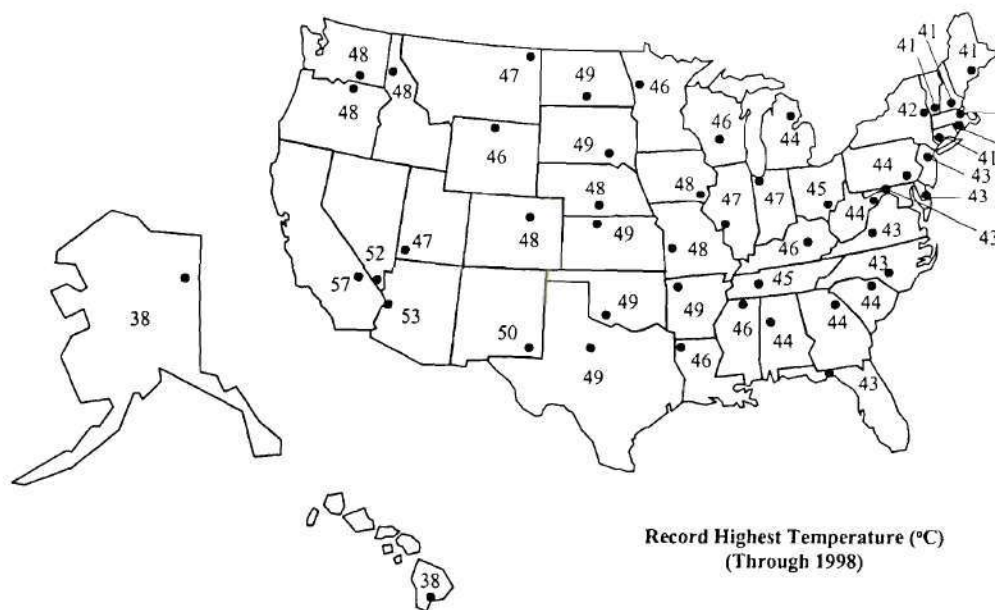


Figure 6. Record Highest Temperature (°C) by States (Source: NCDC)

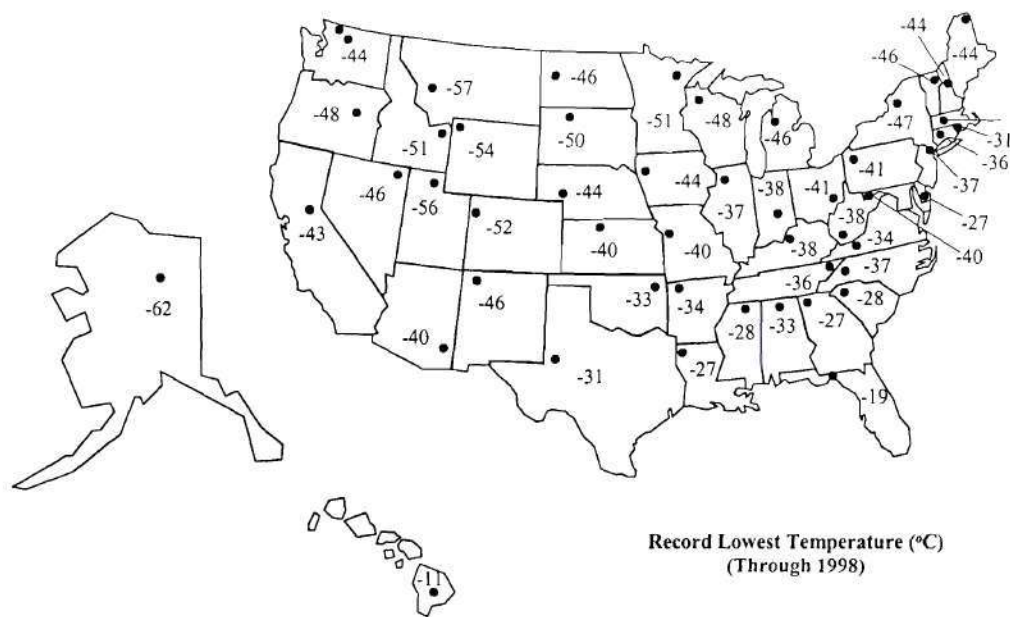


Figure 7. Record Lowest Temperature (°C) by States (Source: NCDC)

To appropriately select the polymeric composite most suitable for strengthening purposes, the designer will rely upon the dimensional stability, strength and stiffness properties of the materials for which the main determinant is their glass transition temperature, T_g . The glass transition temperature is defined as the approximate temperature value or temperature range at which the matrix changes from a glassy to a rubbery state. Above T_g , the composite softens and loses its mechanical properties as illustrated in Figure 8. In addition, it is to be noted that T_g decreases as the moisture content in the composite increases. The glass transition temperature of the resin when cured in a manner similar to that recommended for use in rehabilitating the structure should be at least 30°C (86°F) above the record highest temperature shown in Figure 6. We note that measurements on actual structures strengthened with carbon fiber composites showed that the composite surface temperature was approximately 15°C to 20°C higher

than the air temperature. In addition, polymers with a glass transition temperature of less than 55°C (131°F) must be avoided in rehabilitating civil engineering structures because their mechanical properties degrade under various service environmental conditions. For example, the bond strength in a concrete beam reinforced externally with carbon/epoxy composites having $T_g = 52^{\circ}\text{C}$ (126°F) is reduced by almost 40% when the temperature rises from 20°C (68°F) to 60°C (140°F).

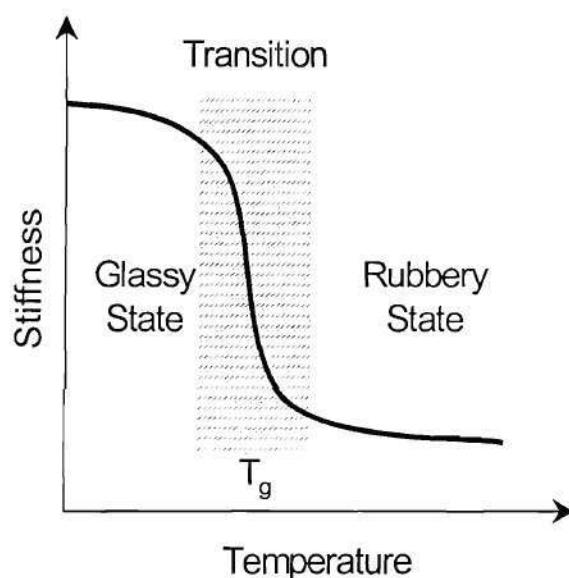


Figure 8. Above the glass transition temperature, T_g , the composite softens

FRP - REINFORCED CONCRETE BEHAVIOR

The failure mode of a FRP rehabilitated reinforced concrete member depends on whether the failure is flexural, shear or axial and on the ratio of steel and FRP reinforcement. In flexure, the member's failure may be controlled by the maximum compressive strain in the concrete (assumed as 0.003), by the maximum usable strain in the FRP, or by the FRP-to-concrete bond. In shear, the failure typically is controlled by the strain in the FRP or by the FRP-to-concrete

bond. Finally, when a composite is used to confine an axial load resisting member, the ultimate failure of the member is controlled by concrete axial strain or by tensile strain in the composite.

Flexure: Figures 9 and 10 illustrate a beam in flexure where a composite is bonded to the bottom tension surface. It is assumed that the reinforced concrete member carries the dead load of the structure and that the rehabilitated beam carries the total factored load. Under an ultimate moment, either strain condition in Figure 9 or in Figure 10 exists; Figure 9 defines failure as crushing of the concrete with a compression strain of 0.003, while Figure 10 defines failure as a maximum, effective ultimate strain in the composite. Note that this effective ultimate strain is a strain less than the tensile breaking strain of the composite. At this time we recommend that the effective tensile ultimate strain for carbon fiber/epoxy composites not exceed 0.005. Under the condition of Figure 9, the full capacity of the concrete in compression is developed, and an equivalent rectangular stress block analysis may be used. The steel reinforcement may or may not be yielding (in the figure it is assumed to yield) ; the composite is elastic. Under the condition of Figure 10, a parabolic stress distribution is assumed for the concrete, such as the Todeschini model (Todeschini et al. 1964), and the composite has reached its maximum, effective ultimate strain. The steel reinforcement typically is yielding. In the rectangular stress block model, Fig-

ure 9, $a = \beta c$ where $\beta = 0.85$ for $f'_c \leq 4000psi$, $\beta = 1.05 - 0.05 \frac{f'_c}{1000}$ for

$4000psi \leq f'_c \leq 8000psi$. and $\beta = 0.65$ for $f'_c \geq 8000psi$. Further, $a = \frac{A_s + T_{FRP}}{0.85f'_c b}$.

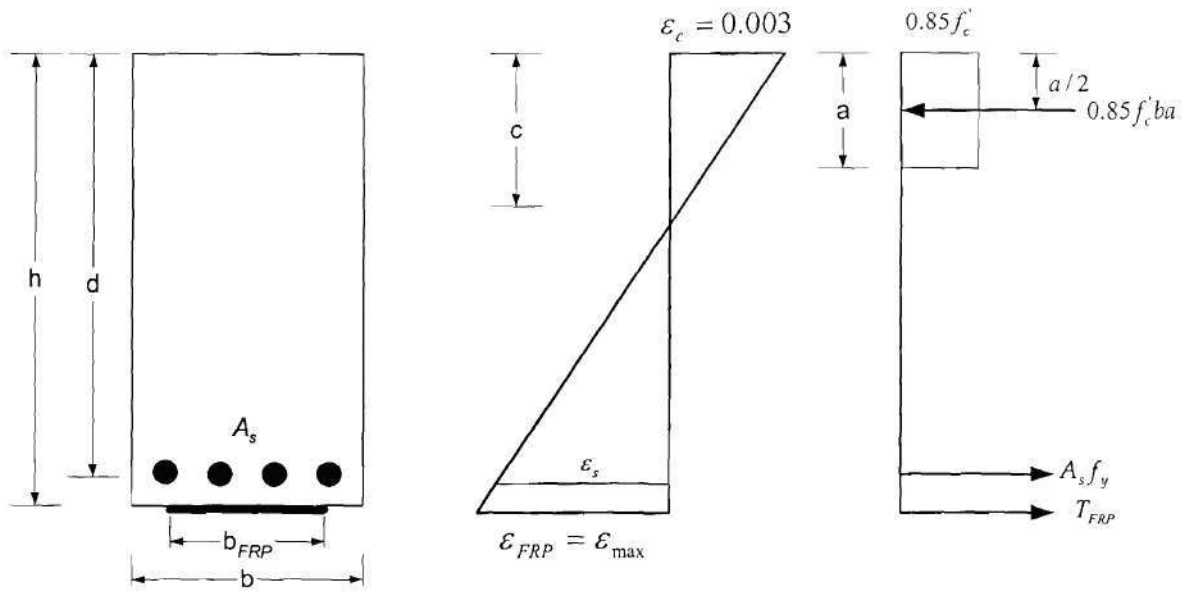


Figure 9. Flexural condition based upon ultimate compressive strain of the concrete

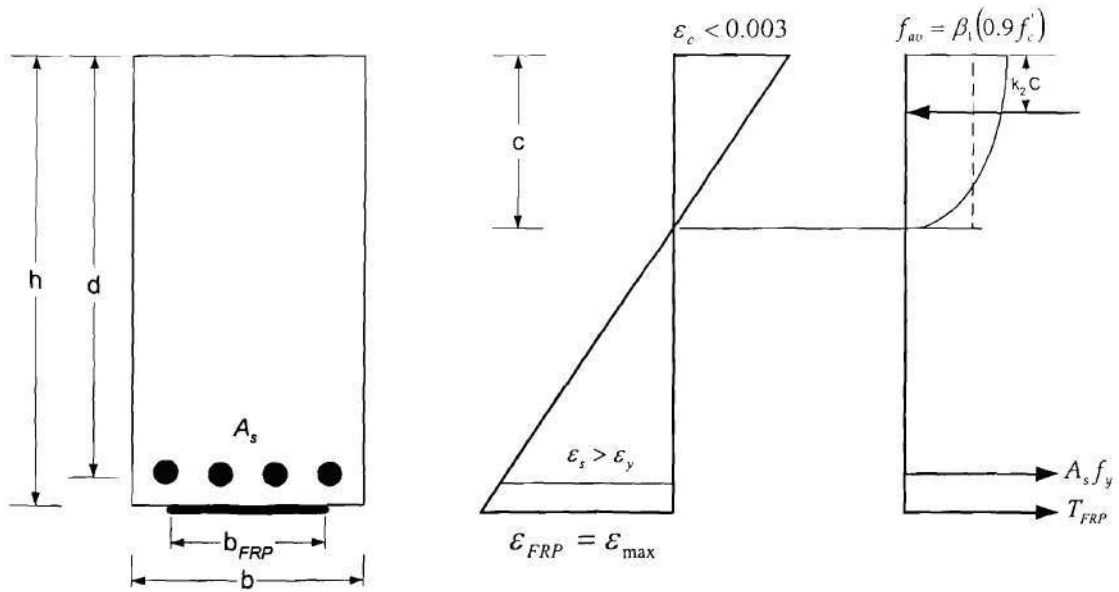


Figure 10. Flexural condition based upon maximum effective ultimate strain in the composite

The nominal moment capacity M_n is

$$M_n = A_s F_y \left(d - \frac{a}{2} \right) + T_{FRP} \left(h - \frac{a}{2} \right) \quad (1)$$

In the Todeschini model, the concrete compressive stress-strain distribution is assumed parabolic according to the following equation:

$$f_c = \frac{2(0.9f'_c)(\epsilon_c/\epsilon_o)}{1 + (\epsilon_c/\epsilon_o)^2} \quad (2)$$

where f_c and ϵ_c are the maximum compressive stress and strain in the concrete, respectively. f'_c is the compressive strength of the concrete and ϵ_o is the strain, corresponding to the maximum stress, computed from the following equation:

$$\epsilon_o = 1.71 \frac{f'_c}{E_c} \quad (3)$$

The modulus of elasticity E_c for normal-weight concrete can be computed from:

$$E_c = 57000 \sqrt{f'_c} \quad (4)$$

where the unit for f'_c is in psi and,

$$E_c = 57000 \sqrt{f'_c} \quad (5)$$

where the unit for f'_c is in MPa.

Based upon equations 2-5 the compressive force in the concrete may be computed from an assumed rectangular stress block having a depth of “c” and an average stress $\beta_1(0.9f'_c)$ as illustrated in Figure 10 , where c is the distance between the neutral axis and the compressive face of the section and β_1 is a factor computed from the following equation:

$$\beta_1 = \frac{\ln \left[1 + \left(\frac{\epsilon_c}{\epsilon_o} \right)^2 \right]}{\left(\frac{\epsilon_c}{\epsilon_o} \right)} \quad (6)$$

The center of gravity of the compression zone is k_2c from the compression surface, where

$$k_2 = 1 - \frac{2 \left[\left(\frac{\epsilon_c}{\epsilon_o} \right) - \tan^{-1} \left(\frac{\epsilon_c}{\epsilon_o} \right) \right]}{\left(\frac{\epsilon_c}{\epsilon_o} \right)^2 \beta_1} \quad (7)$$

Assuming yielding of the steel reinforcement, the nominal moment resistance is then given as

$$M_n = A_s f_y (d - k_2 c) + T_{FRP} (h - k_2 c) \quad (8)$$

Figure 11 illustrates a failure of a slab in flexure where the concrete in compression crushed prior to the delamination of the composite reinforcement. Figures shows a delamination type of failure. An example utilizing the above formulations are given in Appendix A.

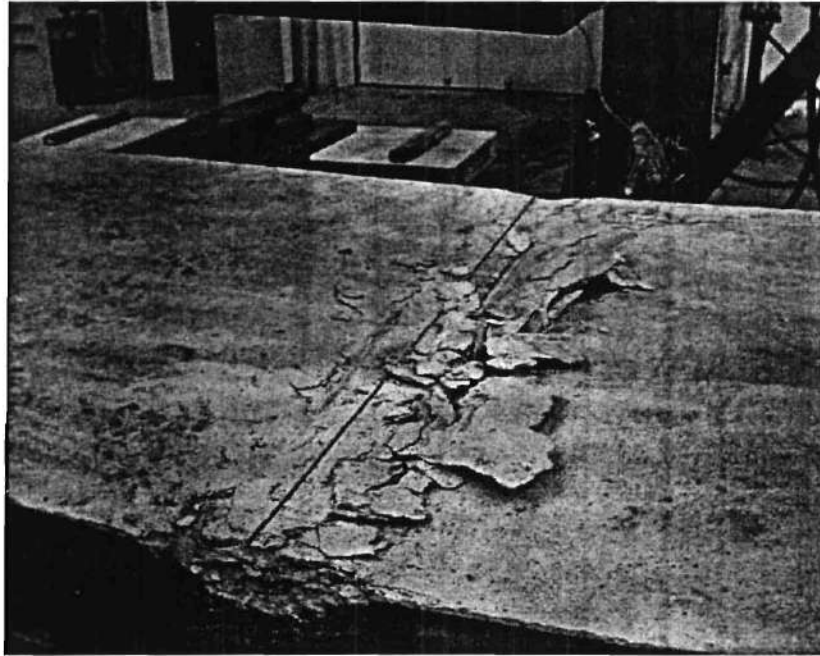


Figure 11. Crushing of concrete deck in flexural failure; FRP tensile reinforcement remained elastic while steel reinforcement yielded.



Figure 12. Delamination of FRP composite from concrete slab in flexural failure. The concrete remaining on the composite indicates good bond.

Shear: FRPs are applied to the side faces of a beam in order to improve the shear strength of the member as shown in Figure 13. The effective ultimate strain for the FRP in this shear condition is 0.004. When the ultimate strain is limited to this value, it may be assumed that the concrete, transverse steel shear reinforcement, and FRP materials act together to provide shear strength as given by

$$V_n = V_c + V_s + V_{FRP} \quad (9)$$

At that effective ultimate strain, the steel stirrups are yielding and the concrete strength may be taken as

$$V_c = \frac{\sqrt{f'_c}}{6} b_w d \quad (10)$$

where the unit of f'_c is in MPa or

$$V_c = 2\sqrt{f'_c} b_w d \quad (11)$$

where f'_c is in psi.

$$V_s = \frac{A_v f_y d}{s} \quad (12)$$

where s is the stirrup spacing and A_v is the area of the stirrups crossing one diagonal crack, and

$$V_{FRP} = \frac{T_{FRP} d_{FRP}}{S_{FRP}} \quad (13)$$

Where T_{FRP} is the strength at a strain of 0.4%, S_{FRP} is the center-to-center spacing of FRP strips, and d_{FRP} is the length of the FRP strips. The strips should be wrapped under the bottom of the section.

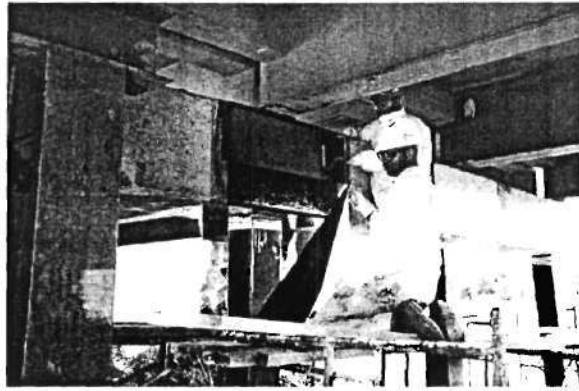


Figure 13. FRP sheet applied to the side of a beam to increase the shear strength

SURFACE PREPARATION

Effective rehabilitation techniques using bonded fiber-reinforced polymeric materials depend strongly upon the condition of the substrate to which composite materials will be bonded. To maximize this bond, it is recommended that at least the following surface preparation procedure be followed:

1. Remove all loose and damaged concrete material by mechanical means. Saw cutting, water blasting, and air hammers are effective as long as "bruising" (added cracking) of surrounding sound concrete is avoided.
2. Repair the corroded reinforcing steel or prestress tendons by mechanically cleaning the rust; high-pressure washing is effective.
3. Restore the shape of the structure with a new structural concrete or mortar system.
4. Round all corner edges of the rehabilitated elements to a minimum radius of 25 mm (1 in.) to permit effective bends in the composite reinforcement.
5. Inject all cracks that are wider than 0.25 mm (0.01 in.) with structural resin.

6. Remove deleterious materials such as laitance, dust, oil, and the likes by means of abrasive blasting. All residue from blasting should be removed with compressed air. When abrasive blasting is not an option due to environmental restrictions, grit blasting where grits and debris are collected by a vacuum system can also be used. Hydroblasting is an effective surface cleaning technique when used the concrete surface shall be allowed to dry prior to any subsequent repair step.

7. Remove all protrusions higher than 1.5 mm (1/16") and fill all holes and depressions greater than 3 mm (1/8") in diameter with structural mortar.

8. Apply a penetrating epoxy primer to the clean dry concrete surface. Apply only when the ambient temperature is between 5° C (40° F) and 32° C (90° F), the relative humidity is less than 90%, the concrete surface temperature is more than 2° C (5° F) above the dew point, and the concrete moisture content is no greater than 4%.

COMPOSITE MATERIAL APPLICATIONS

After allowing the epoxy primer to dry for a period of time as specified by the manufacturer, the rehabilitation procedure may continue provided that the ambient temperature is between 5° C (40° F) and 32° C (90° F), the relative humidity is less than 90%, the concrete surface temperature is more than 2° C (5° F) above the dew point, and the concrete moisture content is dry (moisture content is less than 4%). Elapsed time between mixing and application of the first ply and also between any two successive plies shall be within a time period not exceeding the gel time of the resin.

RECORDS

During the rehabilitation of concrete structures with composite materials, a record of the following data should be kept:

1. Name of the project.
2. Date of strengthening.
3. Ambient air temperature and relative air humidity measured in the shade.
4. Concrete surface temperature and relative humidity at the time of rehabilitation.
5. The compressive strength of the concrete to be strengthened.
6. The commercial designation, name of manufacturer, date of manufacturing, and the manufacturer lot number as shown on the shipping label for each component used to form the binding resin matrix.
7. The commercial designation, name of manufacturer, date of manufacturing, and the manufacturer lot number as shown on the shipping label for the reinforcing fibers, fabric, or prepreg as applicable.

ACCEPTANCE CRITERIA

Within a few days from the rehabilitation, it is recommended that the structure be inspected visually and also by performing a tap test with a coin or a small piece of metal as shown in Figure 14. An automated version of test can be performed with the instrument shown in Figure 15. The structure also can be inspected much more accurately using thermography (Figure 16). The strengthened structure should be free of any defects (e.g. voids, bubbles, and

delamination). In the presence of such defects, a repair of the composite should be done. A valuable destructive test to measure bond strength is the direct composite pull-out test conducted on an area adjacent to the actual rehabilitated area after the manufacturer's recommended curing time period is effective (Figure 17). The test area should have the same number of plies and/or ply orientations as those of the rehabilitated areas; and should not affect the rehabilitation in any manner. The recommended number of composite pull-out tests shall be 3 for every 250 ft² of rehabilitated area. These tests should demonstrate that failure always occurs in either the substrate or along the bond line with a minimum average tensile stress of 300 psi. In addition, it is necessary to conduct test for verifying the glass transition temperature and tensile property in the direction of interest. This can be done on field-prepared panels (Figure 18) that have the same number of plies and fiber orientations and the same curing condition as those of the rehabilitated areas.

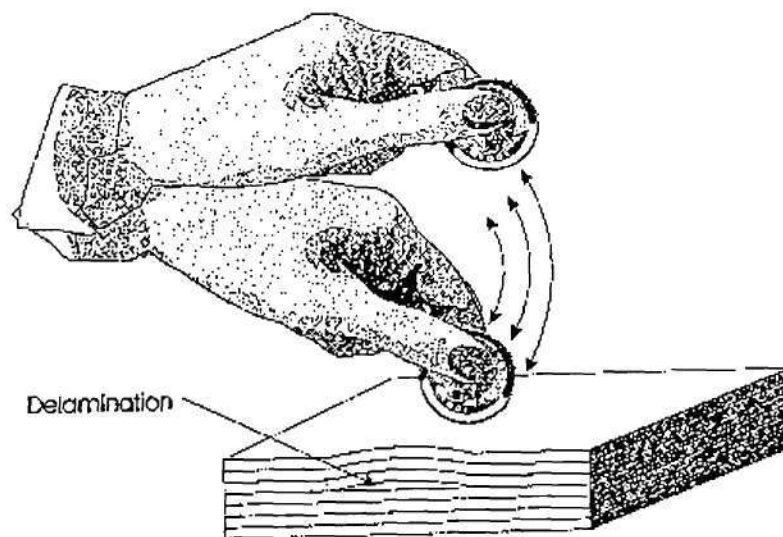


Figure 14. Tap test (Courtesy Abaris Training) for detecting delaminations between the composite layers or between the composite and concrete

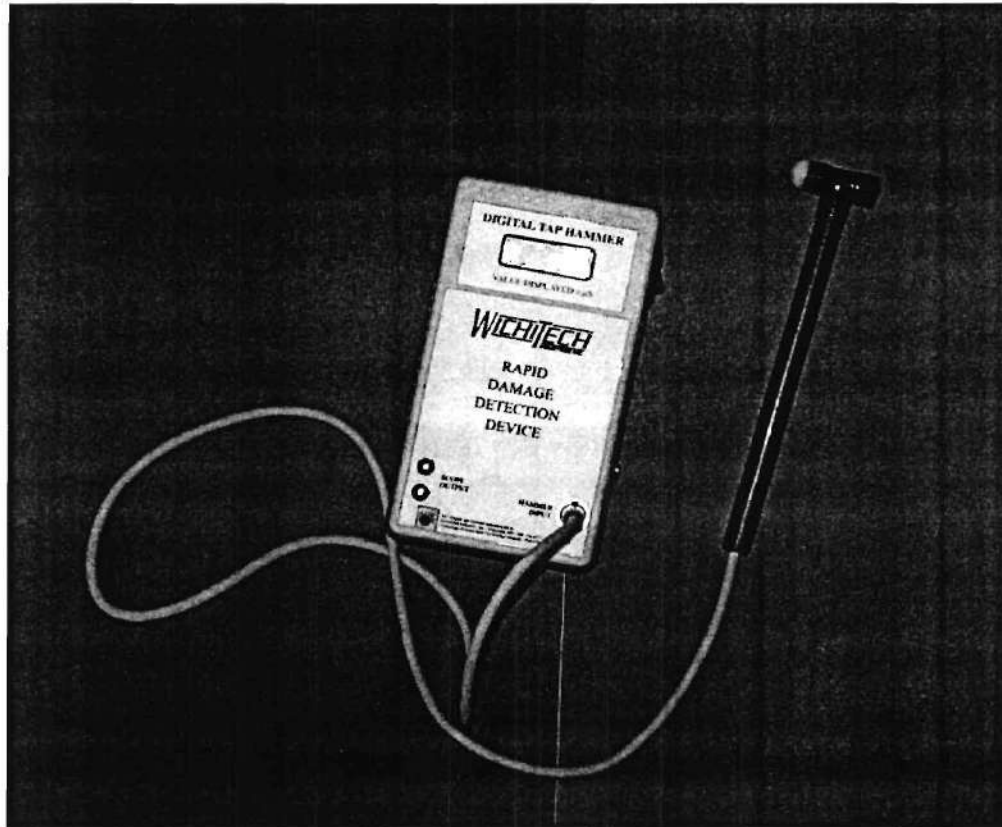


Figure 15. Automated tap hammer for detecting voids and delaminations

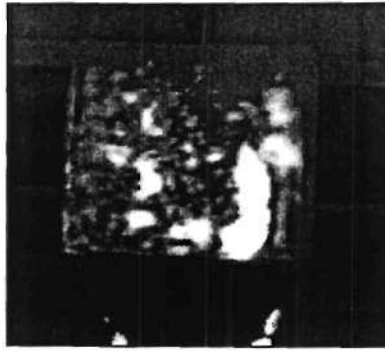


Figure 16. Thermographic image showing delamination

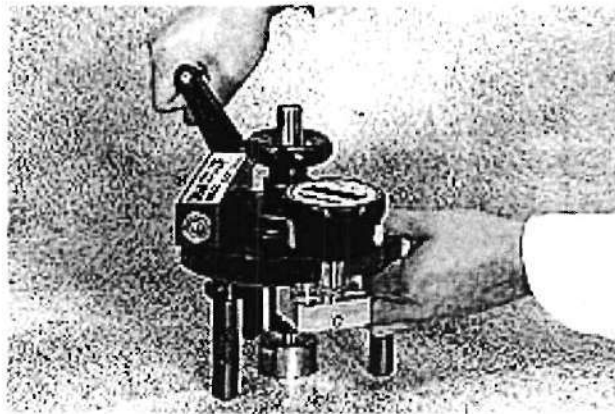


Figure 17. Pull-off Tester (Courtesy of PROCEQ SA)

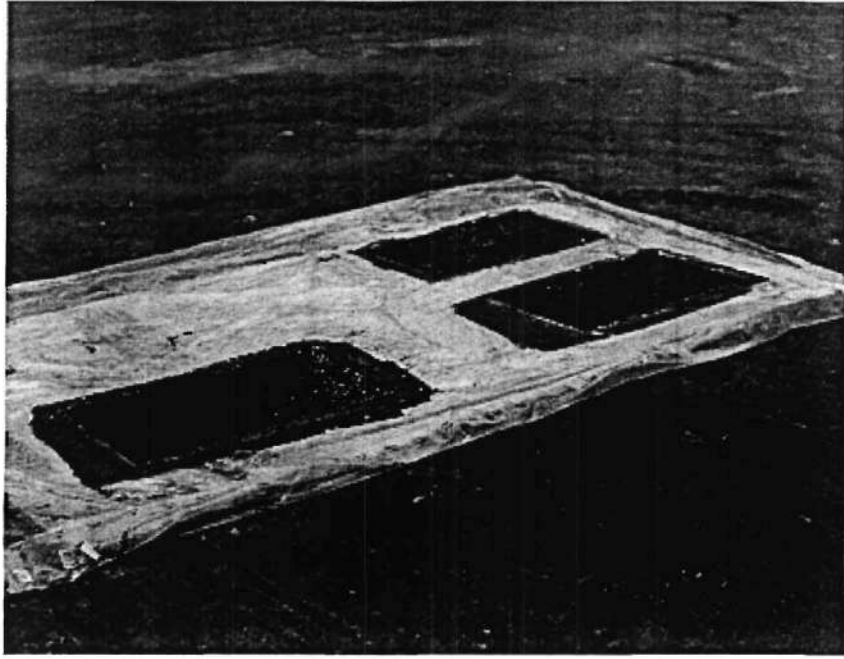


Figure 18. Field-prepared composite panels for material property verifications

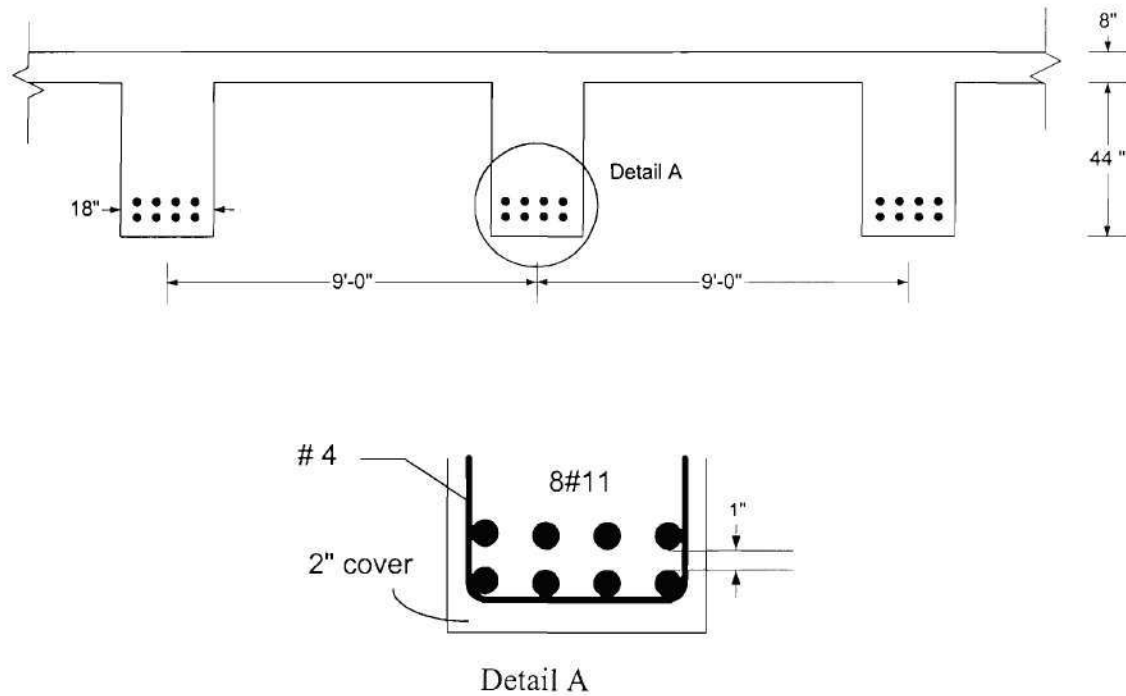
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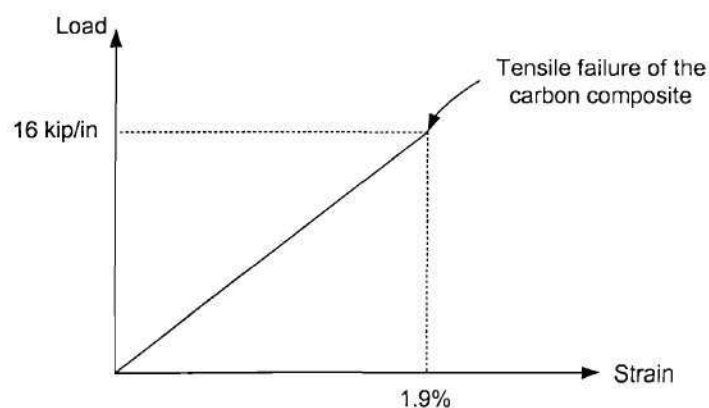
APPENDIX A- EXAMPLE : STRENGTHENING OF A BRIDGE GIRDER

It is required to strengthen the beams in a short-span single lane bridge originally designed for a standard AASHTO truck HS15-44 loading. The span of the bridge is 42' - 8", and the bridge is expected to have sufficient strength for an AASHTO truck HS20-44 loading. Steel reinforcing bars are grade 60, concrete strength is 3,500 psi. Use AASHTO load combination 1A only:

$$1.3\{\beta_D D + \beta_L(L + I)\} = 1.3\{D + 2.2(L + I)\}$$



The polymeric composite used for strengthening is carbon fibers/epoxy manufactured by the pultrusion process. The tensile behavior is described in the following diagram:



Effective flange width:

$$b_e = \text{minimum} \begin{cases} \frac{L}{4} = \frac{42.67}{4} = 128'' \\ 12t + b_w = 12(8) + 18 = 114'' \\ s = 108'' \end{cases}$$

Estimate the dead load:

$$\text{Self-weight} = (0.15) \left(\frac{8 \times 108 + 44 \times 18}{144} \right) = 0.15(11.5) = 1.725 \text{ k/ft}$$

$$\text{Asphalt wearing surface} = (0.02) \left(\frac{108}{12} \right) = 0.18 \text{ k/ft}$$

$$\text{The total dead load} = 1.725 + 0.18 = 1.91 \text{ k/ft}$$

Calculate the dead load moment:

$$M_D = \frac{WL^2}{8} = \frac{1.91(42.67)^2}{8} = 434.7 \text{ k-ft} = 5,216 \text{ k-in}$$

Calculate the impact factor:

$$I = \frac{50}{L + 125} = \frac{50}{42.67 + 125} = 0.3$$

$$\text{Distribution of LL} = \frac{S}{6.5} = \frac{9}{6.5} = 1.385$$

$$M_L^{HS15} = 372.94 \times 1.385 \times 1.3 = 671.5 \text{ lb-ft} = 8,058 \text{ k-in}$$

$$M_u^{HS15} = 1.3[5,216 + 2.2(8,058)] = 29,827 \text{ kip-in} = 2,486 \text{ k-ft}$$

Check the flexural strength of the existing section

$$d = 52'' - 2'' - \frac{1}{2}'' - 1.41 - \frac{1}{2} = 47.5''$$

$$a = \frac{A_s f_y}{0.85 f'_c b} = \frac{12.48 \times 60}{0.85 \times 3.5 \times 108} = 2.33'' \text{ which is smaller than the flange thickness, thus}$$

$$\phi M_n = \phi A_s f_y \left(d - \frac{a}{2} \right) = 0.9 \times 12.48 \times 60 \times \left(47.5 - \frac{2.33}{2} \right) = 31,226 k-in = 2,602 k-ft$$

Because $\phi M_n = 2,602 k-ft > M_u^{HS15} = 2,486 k-ft$, the section is adequate for HS15-44 loading.

Calculate the factored moment resulting from HS20-44

$$M_L^{HS20} = 497.2 \times 1.385 \times 1.3 = 895.3 lb-ft = 10,743 k-in$$

$$M_u^{HS20} = 1.3[5,216 + 2.2(10,743)] = 37,506 k-in = 3,126 k-ft$$

Therefore, the girder must carry an increased ultimate moment:

$$M_{add} = M_u^{HS20} - M_u^{HS15} = 37,506 - 29,827 = 7,679 k-in$$

which represents a 26 % increase.

Estimate the ultimate force to be resisted by the carbon strip

assuming a lever arm of 0.75 h

$$T_{Carbon} = \frac{M_{add}}{0.75h} = \frac{7,679}{0.75(52)} = 196 kips$$

If we limit the strain in the carbon fiber composite at ultimate to 0.5%, the corresponding resistance is:

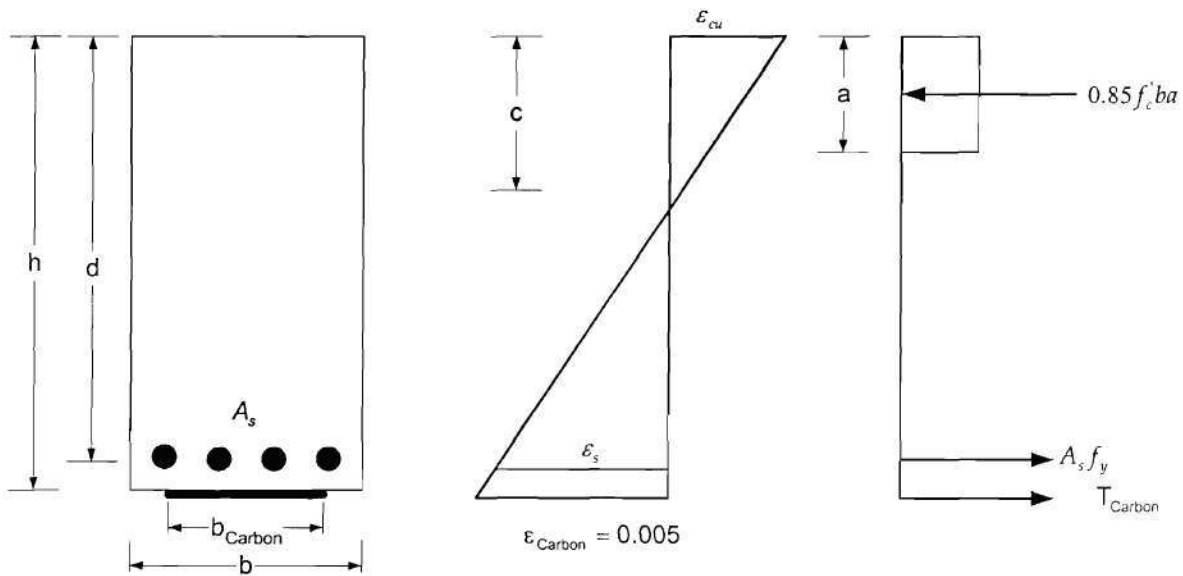
$$R_{Carbon} = \frac{0.005}{\epsilon_1^u} F_1^u = \frac{0.005}{0.019}(16) = 4.2 kip/in \text{ width}$$

Required width:

$$b_{carbon} = \frac{T_{Carbon}}{R_{Carbon}} = \frac{196}{4.2} = 47 in$$

Try 3 layers over the entire width ($3 \times 16 = 48 in$)

Assume a rectangular stress block and concrete crushing, perform force equilibrium:



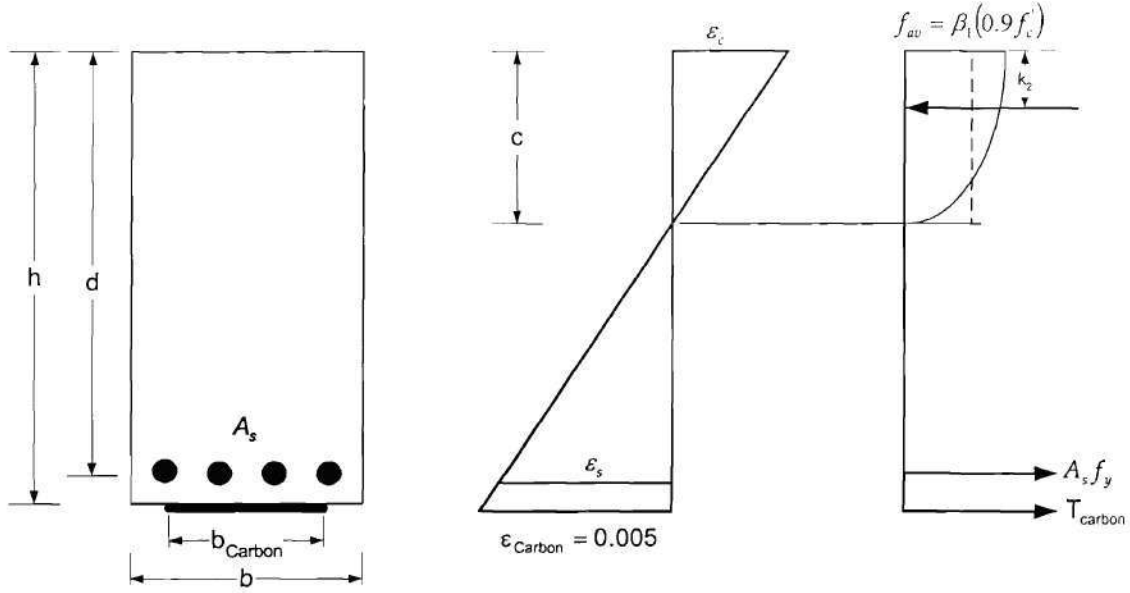
$$a = \frac{A_s f_y + T_{carbon}}{0.85 f'_c b} = \frac{12.48 \times 60 + 3 \times 16 \times 4.2}{0.85 \times 3.5 \times 108} = 2.96 in$$

$$c = \frac{a}{\beta_1} = \frac{2.96}{0.85} = 3.48 in$$

From strain compatibility analysis

$$c = \frac{\epsilon_{cu}}{\epsilon_{cu} + \epsilon_{Carbon}} h = \frac{0.003}{0.003 + 0.005} \times 52 = 19.5 in$$

Because the distance c computed from the strain compatibility analysis is larger than that obtained from the rectangular stress block equilibrium method, the actual strain in the concrete at ultimate is less than 0.003. This means that concrete does not crush, and thus, a parabolic stress distribution is more appropriately assumed as shown below:



Iteration 1:

Assume $c = 7.6$ in, a value between the two extremes, $c = 3.48$ in. and 19.5 in.

$$\epsilon_c = \frac{c}{h-c} \epsilon_{Carbon} = \frac{7.6}{52-7.6} \times 0.005 = 0.0008558$$

$$E_c = 57000 \sqrt{f_c} = 57,000 \sqrt{3,500} = 3,372,000 \text{ psi} = 3,372 \text{ ksi}$$

$$\epsilon_o = 1.71 \frac{f_c}{E_c} = 1.71 \times \frac{3500}{3372000} = 0.001775$$

$$\frac{\epsilon_c}{\epsilon_o} = \frac{0.0008558}{0.001775} = 0.482$$

$$\beta_1 = \frac{\text{Ln} \left[1 + \left(\frac{\epsilon_c}{\epsilon_o} \right)^2 \right]}{\left(\frac{\epsilon_c}{\epsilon_o} \right)} = \frac{\text{Ln} [1 + (0.482)^2]}{(0.482)} = 0.433$$

Compression force:

$$C_c = 0.9f'_c \beta_1 c b = 0.9 \times 3.5 \times 0.433 \times 7.6 \times 108 = 1,119.5 \text{ kips}$$

Tension force:

Check the strain in the steel:

$$\varepsilon_s = \frac{d-c}{h-c} \varepsilon_{Carbon} = \frac{47.5-7.6}{52-7.6} \times 0.005 = 0.0045 > \varepsilon_y = 0.002$$

Therefore steel is yielding

$$T = A_s f_y + T_{carbon} = 12.48 \times 60 + 3 \times 16 \times 4.2 = 950.4 \text{ kips}$$

Because tension force is less than compression force, the area of concrete in compression must be reduced; therefore, reduce the value of c.

Iteration 2

Try c = 6.0 inch

$$\varepsilon_c = \frac{c}{h-c} \varepsilon_{Carbon} = \frac{6}{52-6} \times 0.005 = 0.00065$$

$$\frac{\varepsilon_c}{\varepsilon_o} = \frac{0.00065}{0.001775} = 0.367$$

$$\beta_1 = \frac{\text{Ln}\left[1 + \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2\right]}{\left(\frac{\varepsilon_c}{\varepsilon_o}\right)} = \frac{\text{Ln}[1 + (0.367)^2]}{(0.367)} = 0.344$$

Compression force:

$$C_c = 0.9f'_c \beta_1 c b = 0.9 \times 3.5 \times 0.344 \times 6 \times 108 = 702 \text{ kips} \text{ which is smaller than the tension force of 950.4 kips.}$$

Iteration 3

Try $c = 7$ inch

$$\epsilon_c = \frac{c}{h-c} \epsilon_{Carbon} = \frac{7}{52-7} \times 0.005 = 0.00077$$

$$\frac{\epsilon_c}{\epsilon_o} = \frac{0.00077}{0.001775} = 0.438$$

$$\beta_1 = \frac{Ln\left[1 + \left(\frac{\epsilon_c}{\epsilon_o}\right)^2\right]}{\left(\frac{\epsilon_c}{\epsilon_o}\right)} = \frac{Ln[1 + (0.438)^2]}{(0.438)} = 0.4$$

Compression force:

$C_c = 0.9f'_c \beta_1 c b = 0.9 \times 3.5 \times 0.4 \times 7 \times 108 = 952.6 \text{ kips}$ which is approximately equal to the tension force of 950.4 kips.

Compute the moment resistance about center of compression force:

$$k_2 = 1 - \frac{2\left[\left(\frac{\epsilon_c}{\epsilon_o}\right) - \tan^{-1}\left(\frac{\epsilon_c}{\epsilon_o}\right)\right]}{\left(\frac{\epsilon_c}{\epsilon_o}\right)^2 \beta_1} = 1 - \frac{2[(0.438) - \tan^{-1}(0.438)]}{(0.438)^2(0.4)} = 0.344$$

$$k_2 c = 0.344 \times 7 = 2.408 \text{ in}$$

$$\phi M_n = \phi A_s f_y (d - k_2 c) + T_{carbon} (h - k_2 c)$$

$$\phi M_n = 0.9 \times 12.48 \times 60 (47.5 - 2.408) + 3 \times 16 \times 4.2 \times (52 - 2.408)$$

$$\phi M_n = 40,386 \text{ k-in} = 3,365 \text{ k-ft}$$

$$\phi M_n = 3,365 \text{ k-ft} > M_u^{HS20} = 3,126 \text{ k-ft}$$

Use 3 layers over the entire width.

Bond and anchorage

$$f_{bond} = 350 \text{ psi}$$

$$L_d = \frac{\text{Force in CFRC}}{f_{bond} \times \text{width}} = \frac{3 \times 16 \times 4,200}{350 \times 16} = 36''$$



Mid-America Earthquake Center

Headquartered at the University of Illinois at Urbana-Champaign

ST-16 Innovative Materials for Bridge Retrofit

Guidelines Polymeric Composite Materials for Rehabilitating Reinforced Concrete Structures

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Georgia Institute of Technology
School of Civil and Environmental Engineering
Atlanta, GA 30332

June 2000

1.0 SCOPE

This specification defines the requirements for polymeric composite material systems intended for use for rehabilitating reinforced concrete structures.

2.0 TERMINOLOGY

Descriptions of terms pertaining to this specification shall be those of ASTM D3878 Standard Terminology of High-Modulus Reinforcing Fibers and Their Composites and of ASTM D883 Terminology Relating to Plastics. When definitions of terms are conflicting, those of ASTM D3878 shall have the precedence over those in ASTM D883.

3.0 MATERIAL DATA FOR SUBMISSION

Based on previous use demonstrating satisfactory performance under specified conditions approximating the conditions of use, contractors shall furnish the user the following information pertaining to the matrix (binding resin or adhesive), reinforcement, and composite systems.

3.1 MATRIX MATERIAL

3.1.1. The commercial designation, name of manufacturer, and Material Safety Data Sheet (MSDS), prepared in compliance with the Federal OSHA Hazard Communication Standard 29 CFR 1910.59, of the matrix material and any of its component.

3.1.2. The density of the matrix material or any of its components determined according to ASTM D792 Test Methods for Specific Gravity and Density of Plastics by Displacement.

3.1.3. The gel time determined according to ASTM D2472 Standard Test Method for Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins.

3.1.4. The curing behavior determined according to ASTM D 4473 Standard Practice for Measuring the cure Behavior of Thermosetting Resins Using Dynamic Mechanical Procedures

3.1.5. The water absorption determined according to ASTM D 570 Standard Test Method for water Absorption of Plastics.

3.1.6. The glass transition temperature according to ASTM E 1356 Test Method for Glass Transition Temperatures by Differential Scanning Calorimetry or Differential Thermal Analysis.

3.1.7. The tensile properties according to ASTM D638 Standard Test Method for Tensile Properties of Plastics

3.1.8. The compressive properties according to ASTM D695 Standard Test Method for Compressive Properties of Rigid Plastics

3.1.9. The shear strength according to ASTM D732 Standard Test Method for Shear Strength of Plastics by Punch Tool

3.1.10. The flexural properties according to ASTM D790 Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

3.2 REINFORCEMENT

3.2.1. The commercial designation, name of manufacturer, and fiber form (e.g. yarns, strands, tows, fabric, and prepreg), the fiber orientation, fiber dimensions, and fiber surface treatments.

3.2.2. The density of the fiber according to ASTM D 3800 Standard Test Method for Density of High-Modulus Fibers.

3.2.3. For prepregs, the matrix solid content and matrix content shall be determined according to ASTM D3529 "Standard Test Method for Matrix Solids Content and Matrix content of Composite Prepreg."

3.2.4. For epoxy/carbon fiber based prepreg, the volatiles content shall be reported according to ASTM D 3530 "Volatiles Content of Carbon-Fiber Prepreg."

3.3 COMPOSITE SYSTEM

For a fully cured composite system, the following materials properties determined experimentally by an independent laboratory shall be provided.

3.3.1. The density according to ASTM D792 Test Methods for Specific Gravity and Density of Plastics by Displacements.

3.3.2. The fiber volume according to ASTM D2584 Test Method for Ignition Loss of Cured Reinforced Resins.

3.3.3. The void volume according to ASTM D2734 Test Method for Void Content of Reinforced Plastics." D 3171 Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion.

3.3.4. The glass transition temperature according to ASTM E 1356 Test Method for Glass Transition Temperatures by Differential Scanning Calorimetry or Differential Thermal Analysis.

3.3.5. Moisture diffusivity and absorption or desorption properties according to ASTM D5229 “Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials.”

3.3.6. The tensile properties (ultimate strength, ultimate strain, and modulus) of the composite materials according to ASTM D3039 “Test Method for Tensile Properties of Polymer Matrix Composite Materials.”

4.0 MATERIALS QUALIFICATIONS

4.1. Contractors shall submit for approval testing results, generated by independent laboratories, showing that the carbon fibers, the binding resin matrix, and the composite system, referenced in the appropriate Section below, possess minimum physical and mechanical property values determined by a testing laboratory. For each property value, the number of batches from which test specimens were drawn, the number of tested specimens from each batch, the mean value, the minimum value, the maximum value, and the coefficient of variation shall be reported. The number of tested samples shall be as required by the pertinent standard test method referenced in Section 3.0.

4.1.1. Carbon Fibers: The minimum values of the axial tensile strength, strain, and modulus shall be 500 ksi (3,400 MPa), 1.5%, and 29,000 ksi (200,000 MPa), respectively, determined in accordance with ASTM D3800.

4.1.2. Binding Resin Matrix: The minimum values of the axial tensile rupture strength, rupture strain, and modulus of the binding resin matrix shall be 7,200 psi (50 MPa), 3.5%, and 435 ksi (3000 MPa), respectively, determined in accordance with ASTM D638. The glass transition temperature of the resin when cured in a manner similar to that recommended for use shall not be less than 65°C (150° F).

4.1.3. Composite Material System: The minimum axial tensile strength per unit width, strain, and modulus in the fiber direction of unidirectionally reinforced composites shall be 3 kip/in (530 N/MM.), 0.8%, and 9,000 ksi (62,000 MPa), respectively, determined in accordance with ASTM D3039. The maximum moisture content of the composite material at the equilibrium condition shall not exceed 3%.

4.1.4. The glass transition temperature determined in accordance with ASTM E1356, the tensile properties of the composite in the direction of interest determined in accordance with ASTM D3039, and the tensile and flexural properties of the resin determined in accordance with ASTM D638 and ASTM D790, respectively shall retain 85% of baseline values obtained from laboratory tests conducted as per Section 3.0 after conditioning in the following environments:

4.1.4.1. Water: Samples shall be immersed in distilled water having a temperature of $100 \pm 3^{\circ}F$ and tested after 1,000, 3000, and 10,000 hours of exposure.

4.1.4.2. Alternating Ultraviolet light and condensating humidity: Samples shall be exposed to 100 alternating ultraviolet lumen intensity and condensating humidity cycles using FS 40 UV-B bulbs in an apparatus meeting the requirements of ASTM G53. Each cycle shall consist of four hours at $140^{\circ}F$ and four hours of condensate exposure at $104^{\circ}F$. Samples shall be tested as soon as possible after removal from the apparatus.

4.1.4.3. Salt Water: Samples shall be conditioned according to ASTM D1141 "Standard Specification for Substitute Ocean water."

4.1.4.4. Alkali: Samples shall be immersed in a saturated solution of calcium hydroxide (PH 9.5) at ambient temperature of $23 \pm 3^{\circ}C$ ($73 \pm 5^{\circ}F$) for 1,000, 3,000, and 10,000 hours prior to testing. The PH level shall be monitored at regular intervals, and the solution shall be changed as needed.

4.1.4.5. Fuel: Samples shall be immersed in for four hours and then tested after removal from the environment.

4.1.4.6. Freeze-Thaw: Composite panels or coupons shall be exposed to 100 repeated cycles of freezing and thawing in an apparatus meeting the requirements of ASTM C 666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing."

5.0 FIELD APPLICATION

5.1 SURFACE EVALUATION

Concrete surfaces to be repaired with composite materials shall exhibit a minimum of 200 psi pullout strength when tested in accordance with Appendix A of "Use of Epoxy Compounds with Concrete" prepared by ACI Committee 503.

5.2 SURFACE PREPARATION

Holes and depressions in the concrete surface to be repaired with polymer composite materials shall be filled flush with mortar approved by the Georgia Department of Transportation. Cracks shall be epoxy injected. Corner edges shall be rounded to a minimum radius of 1 in. (25 mm). The concrete surface to which composite materials is to be applied shall be sand-blasted to remove any deleterious materials such as laitance, dust, oil, or loose materials. All residue from sandblasting shall be removed with compressed air only. A penetrating epoxy primer may or may not be applied to the clean concrete sur-

face prior to the repair application with composite materials. The requirement for priming will depend on the composite system used. When used, priming shall be performed only when the air and surface temperatures are 50° F (10° C) or above and when the concrete surface moisture level determined from field measurements is no more than 10%.

5.3 COMPOSITE MATERIAL APPLICATION

Composite materials shall be applied only to a primed cured (as applicable) concrete surface that is clean and free of dust. Work shall be performed when the air and surface temperatures are 50° F (10° C) or above and the moisture in the concrete surface is below 10%. Elapsed time between mixing and application of the first ply and also between any two successive plies shall be within a time period not exceeding the gel time as per Section 3.1.

6.0 RECORDS

During the rehabilitation of concrete structures with composite materials, the Contractor shall record the following data:

- 6.1. Name of the project.
- 6.2. Date of strengthening.
- 6.3. Ambient air temperature and relative air humidity measured in the shade.
- 6.4. Concrete surface temperature and relative humidity at the time of rehabilitation.
- 6.5. The compressive strength of the concrete to be strengthened.
- 6.6. The commercial designation, name of manufacturer, date of manufacturing, and the manufacturer lot number as shown on the shipping label for each component used to form the binding resin matrix.
- 6.7. The commercial designation, name of manufacturer, date of manufacturing, and the manufacturer lot number as shown on the shipping label for the reinforcing fibers, fabric, or prepreg as applicable.

7.0 ACCEPTANCE CRITERIA

7.1. The strengthened structure shall be free of any defects (e.g. voids, bubbles, and delamination). In the presence of such defects, the Contractor shall submit a repair plan before any repair work begins.

7.2. The Contractor shall be responsible for conducting direct composite pull-out tests referenced in Section 5.1 to be performed on areas adjacent to the actual rehabilitated area after the manufacturer's recommended curing time period. The test area shall have the same number of plies and/or ply orientations as those of the rehabilitated areas; and shall not affect the rehabilitation in any manner. The required number of composite pull-out tests shall be 3 for every 250 ft² of rehabilitated area.

These tests shall demonstrate that failure always occurs in either the substrate or along the bond line with a minimum average tensile stress of 300 psi.

7.3. The Contractor shall be responsible for conducting tensile material property tests in the primary fiber direction. The Contractor shall submit a plan for the preparation of these tests. The tests shall be in accordance with ASTM D3039 and the results shall meet the requirements of Section 4.1.3.

7.4. The Contractor shall be responsible for conducting glass transition temperature tests in accordance with ASTM E 1356. A minimum of three tests for every 250 ft² of strengthened area shall be required. Results shall meet the requirements of Section 4.1.2.